

Surface Water Quality

Effects of Near-Surface Hydraulic Gradients on Nitrate and Phosphorus Losses in Surface Runoff

Fen-Li Zheng,* Chi-Hua Huang, and L. Darrell Norton

ABSTRACT

Phosphorous (P) and nitrogen (N) in runoff from agricultural fields are key components of nonpoint-source pollution and can accelerate eutrophication of surface waters. A laboratory study was designed to evaluate effects of near-surface hydraulic gradients on P and N losses in surface runoff from soil pans at 5% slope under simulated rainfall. Experimental treatments included three rates of fertilizer input (control [no fertilizer input], low [40 kg P ha⁻¹, 100 kg N ha⁻¹], and high [80 kg P ha⁻¹, 200 kg N ha⁻¹]) and four near-surface hydraulic gradients (free drainage [FD], saturation [Sa], artesian seepage without rain [Sp], and artesian seepage with rain [Sp + R]). Simulated rainfall of 50 mm h⁻¹ was applied for 90 min. The results showed that near-surface hydraulic gradients have dramatic effects on NO₃-N and PO₄-P losses and runoff water quality. Under the low fertilizer treatment, the average concentrations in surface runoff from FD, Sa, Sp, and Sp + R were 0.08, 2.20, 529.5, and 71.8 mg L⁻¹ for NO₃-N and 0.11, 0.54, 0.91, and 0.72 mg L⁻¹ for PO₄-P, respectively. Similar trends were observed for the concentrations of NO₃-N and PO₄-P under the high fertilizer treatment. The total NO₃-N loss under the FD treatment was only 0.01% of the applied nitrogen, while under the Sp and Sp + R treatments, the total NO₃-N loss was 11 to 16% of the applied nitrogen. These results show that artesian seepage could make a significant contribution to water quality problems.

PHOSPHORUS AND NITROGEN in runoff from agricultural lands are nonpoint sources of pollution and can accelerate eutrophication of surface waters (Daniel et al., 1994, 1998; Foy and Withers, 1995). Long-term applications of P and N in chemical fertilizers and animal wastes have resulted in elevated levels of soil P and N in many locations in the United States (Lovejoy et al., 1997). Soils high in P and N have aggravated water pollution problems in many areas. Damage to surface water quality, due to sedimentation and excessive nutrients from agricultural lands in the United States, was estimated to range from \$2.2 to \$7 billion dollars annually (Lovejoy et al., 1997). Extensive research efforts have identified and quantified factors contributing to chemical losses in runoff, such as soil properties, crop residue cover, slope, tillage, method and timing of fertilizer application, and

rainfall pattern (Alberts and Spomer, 1985; Hubbard and Sheridan, 1983; Hubbard et al., 1991; Lowrance, 1992; Pote et al., 1996, 1999). These research findings enhance the understanding of how P and N are moved from soil to water bodies and help the development of management practices capable of minimizing the excessive nutrient problem.

Due to its high solubility, NO₃-N tends to be transported in drainage and subsurface flow. In southern Georgia, Hubbard and Sheridan (1983) reported that 20% of the applied N over a 10-yr period was lost in surface runoff and subsurface flow, and 99% of this loss occurred in subsurface flow. Other studies by Hubbard et al. (1991) and Lowrance (1992) at the same watershed and elsewhere by Alberts and Spomer (1985) with different crops showed the same trend with significantly greater NO₃-N movement in subsurface flow than in surface runoff.

Because P is strongly bound in soil and much less mobile than N, many efforts have been focused on relating different soil test P values to P in surface runoff (Daniel et al., 1993; Pote et al., 1996, 1999; Sharpley et al., 1996; Cox and Hendricks, 2000). Despite a general positive correlation between soil test P to runoff P, the slope of the trend line varied with methods of P extraction, soil type, organic matter, and soil management. Recent studies had been initiated to couple watershed hydrology and chemical transport using the variable source area (VSA) concept (Gburek and Sharpley, 1998; Gburek et al., 2000). Gburek and Sharpley (1998) studied P loss in east-central Pennsylvania and showed that zones of runoff production, and consequently, the areas that ultimately controlled most P transport, were the near-stream saturated areas of the watershed. Further analysis showed that most in-stream P came from soils within 60 m of the stream, rather than from the entire area of the watershed (Gburek et al., 2000).

In this study, we hypothesized that because most agricultural chemicals are in the surface layer, the near-surface hydraulic gradients could have a large influence on chemical transport. This study was initiated based on recent laboratory findings of increased sediment delivery and rilling from soil subject to saturation and artesian seepage or exfiltrating through flow (Huang

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Abbreviations: C, control fertilizer treatment (no fertilizer input); L, low fertilizer treatment (40 kg P ha⁻¹, 100 kg N ha⁻¹); H, high fertilizer treatment (80 kg P ha⁻¹, 200 kg N ha⁻¹); FD, free drainage hydraulic gradient; Sa, saturation hydraulic gradient; Sp, artesian seepage without rain hydraulic gradient; Sp + R, artesian seepage with rain hydraulic gradient.

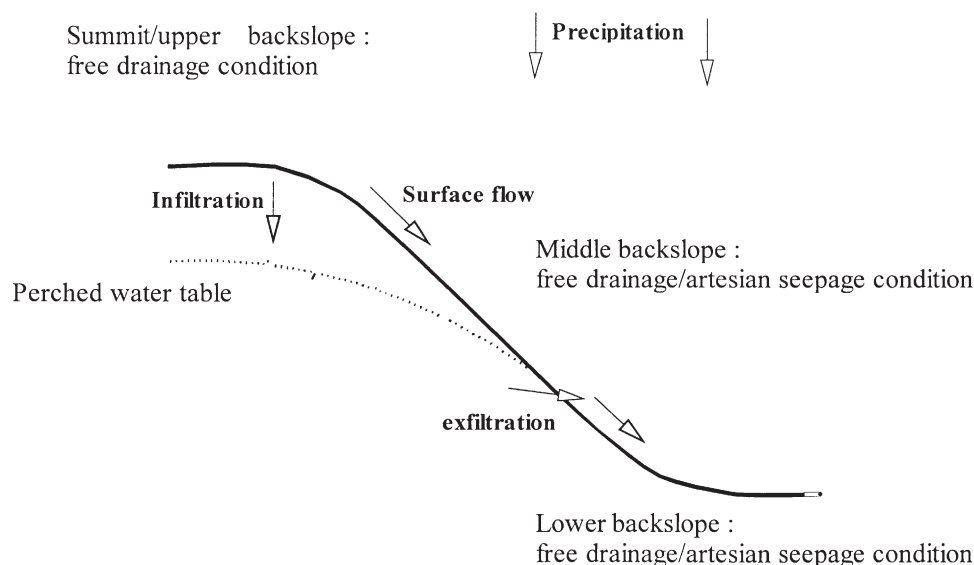


Fig. 1. Hillslope position and hydrologic condition.

and Laflen, 1996; Gabbard et al., 1998; Huang et al., 1999; Zheng et al., 2000). Artesian seepage is a common occurrence during the wet season such as early spring after a wet winter, when the shallow ground water emerges at the soil surface as return flow in the middle or lower portions of the hillslope (Fig. 1). Soils with clayey subsoil or tight plow pan are prone to produce the return flow or seep (Whipkey and Kirkby, 1978; Dunne, 1978).

When a hillslope artesian seepage flow occurs, it flows laterally in the shallow zone above the impervious layer until it seeps out on the surface. The accumulation of nutrients and agricultural chemicals in the topsoil layer increases the potential for artesian seepage to transport chemicals. In addition, the artesian seepage flow occurs only when the soil is saturated. This moisture condition further enhances the availability of dissolved chemicals for transport.

The objective of this study was to quantify the effect of near-surface hydraulic gradients on $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ transport in surface runoff water. A laboratory rainfall simulation study was conducted using a silt loam soil under four different near-surface hydraulic conditions: free drainage (FD), saturation (Sa), artesian seepage without rain (Sp), and artesian seepage with rain (Sp + R).

MATERIALS AND METHODS

Soil Sample Collection and Soil Properties

The soil used in this study was a Waupecan silt loam (fine-silty, mixed, mesic Typic Argiudolls) collected from the surface to a 0.3-m depth near Dayton in Tippecanoe County, Indiana. The collected soil was air-dried and sieved through a 10-mm-opening sieve and stored in covered containers until used in the experiment.

Experimental Setup

The study was conducted on soil pans that were 45 cm long, 32 cm wide, and 35 cm deep. Each soil pan had six drainage

holes at the bottom. A water supply system was designed to supply water to the soil pan from the bottom to control the near-surface hydraulic gradient (Fig. 2). A saturation condition was created when the supply water level was set at the soil surface and an artesian seepage condition was created when the supply water level was set higher than the soil surface, forcing water to flow out of the soil. In this study, the artesian seepage condition was created with the supply water level set 20 cm above the soil surface. For the free drainage treatment, the water supply tubes were not connected to let the soil pan drain freely under gravity.

Two programmable rainfall simulation troughs (Foster et al., 1979), spaced 135 cm apart, were used in this study. Each simulation trough had three VeeJet nozzles (Part no. 80100; Spraying Systems Co., Wheaton, IL) spaced 1.07 m apart. The nozzles were approximately 2.8 m above the soil surface. During the rainfall simulation, the nozzle pressure was kept at 41.4 kPa (6 psi). This rainfall simulator can be set to any preselected rainfall intensity, ranging from 6.3 to 100 mm h^{-1} , by programming the oscillating frequency of the nozzles.

Experimental treatments in this study included three rates of fertilizer input: control (no fertilizer input), low (40 kg P ha^{-1} , 100 kg N ha^{-1}), and high (80 kg P ha^{-1} , 200 kg N ha^{-1}), hereafter designated as C, L, and H, respectively. These fertilizer treatments were subjected to four near-surface hydraulic gradient treatments: free drainage (FD), saturation (Sa), artesian seepage without rain (Sp), and artesian seepage with rain (Sp + R). The detailed experimental treatments appear in Table 1. For each fertilizer level, three replicates were made for rainfall simulation for the FD and Sa treatments, and three additional soil pans were prepared and used to collect the before-run soil profile samples three days after prewetting under free drainage; four replicates were made for the Sp and Sp + R treatments, and four additional soil pans were prepared and used to collect the before-run soil profile samples three days after prewetting under free drainage.

Preparation of Soil Pans

Each soil pan was packed with a 6-cm layer of industrial quartz sand at the bottom and a 24-cm layer of the test soil. Moisture content of the test soil was determined before pack-

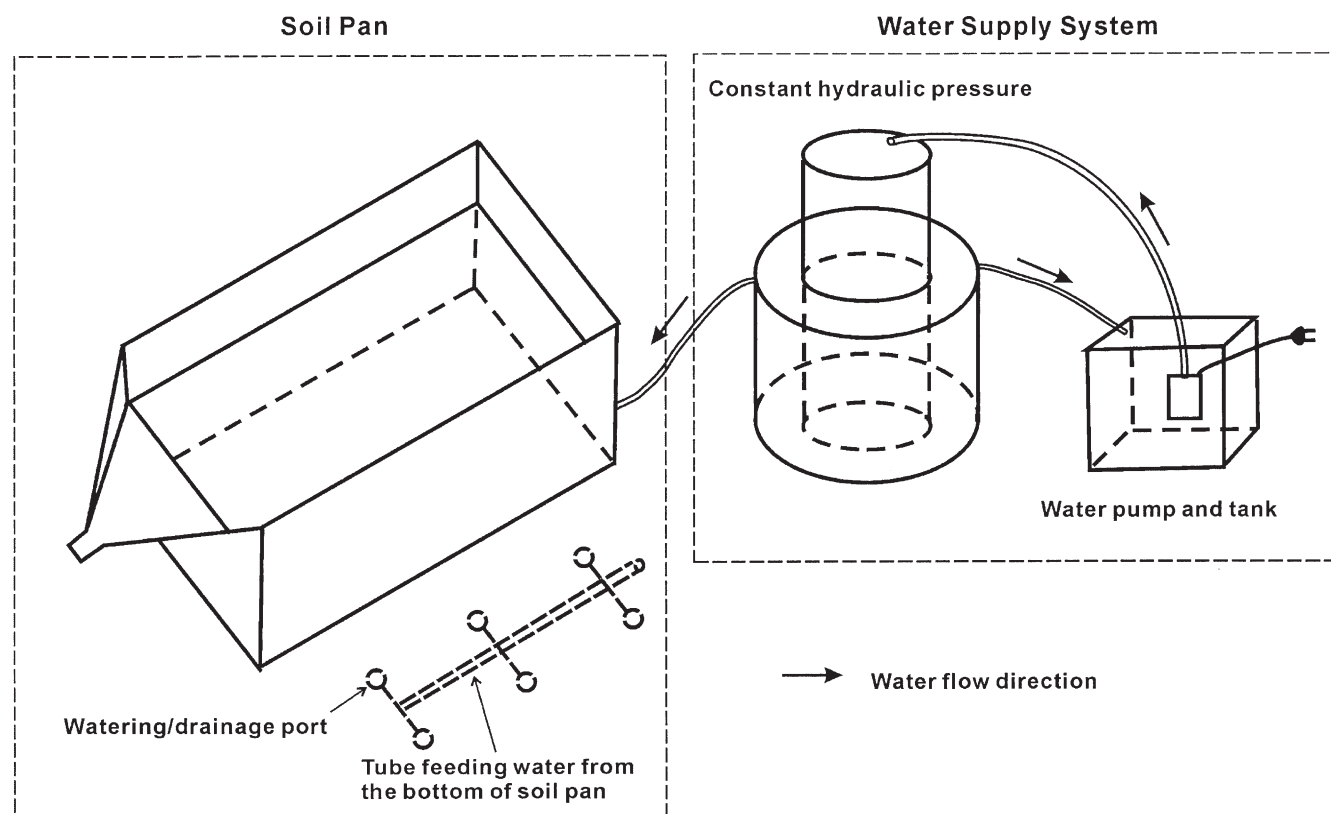


Fig. 2. Experimental setup.

ing of the soil pan to calculate the amount of soil needed to obtain a bulk density of 1.24 g cm^{-3} . The moisture content of the test soil used for packing the pan ranged from 5 to 7% by weight. To ensure uniformity, the soil pan was packed in individual 2-cm layers. For soil pans with fertilizer input, reagent-grade KNO_3 and K_2HPO_4 were thoroughly mixed with the top 2-cm layer of soil before packing. The low fertilizer treatment required 10.39 g KNO_3 and 3.23 g K_2HPO_4 for a pan; the high fertilizer treatment required 20.78 g KNO_3 and 6.46 g K_2HPO_4 for a pan.

After soil pan preparation, a prewetting rain (15 mm of rain at 9.5 mm h^{-1} intensity) was applied at 0% slope. The 9.5 mm h^{-1} rain intensity was selected to avoid the initiation of runoff during the prewetting event. To further avoid raindrop-induced splash and surface sealing, two layers of wire mesh

were placed over the soil surface. This initial rain was applied to allow fertilizer leaching into the soil profile, create a uniform surface soil moisture condition before the experiment, and reduce surface variability from preparation. After the prewetting rain, the soil pan was covered with a plastic sheet and allowed to equilibrate under free-drained conditions for three days.

Rainfall Experiments

Three days after the prewetting rain, soil pans were set to 5% slope and subjected to the experimental hydraulic gradients. A simulated rainstorm of 50 mm h^{-1} for 90 min was applied to the FD, Sa, and Sp + R treatments. For the Sa and Sp + R treatments, the rainfall was applied after the surface was either saturated or when seepage flow started. During rainfall simulation runs, runoff samples were collected at 10-min intervals. For the Sp treatment, due to the small quantity of seepage flow, runoff samples were collected at 15-min intervals for 90 min immediately after the seepage flow started. During each run, the rainfall amount was measured at least twice with a hyetometer on the right and left sides of the soil pan.

Immediately after each run, runoff samples were centrifuged (4000 rpm, 15 min) and filtered through $2.5\text{-}\mu\text{m}$ paper (Whatman [Maidstone, UK] no. 5). The filtered solution was stored in a refrigerator and analyzed 24 h later. Sediment samples at the bottom of the centrifuge bottle were washed into cans, and oven-dried at 55°C . This dry sediment was weighted to calculate sediment delivery.

Collection of Soil Samples from the Soil Pans

Soil samples taken before and after each run were analyzed for moisture and nutrient contents. The before-run soil profile

Table 1. List of experimental treatments.

Fertilizer treatment	Fertilizer input		Hydraulic gradient	Replications
	N	P		
	– kg ha^{-1} –			
Control (C)	0	0	free drainage (FD)	3
C	0	0	saturation (Sa)	3
C	0	0	artesian seepage without rain (Sp)	4
C	0	0	artesian seepage with rain (Sp + R)	4
Low input (L)	100	40	FD	3
L	100	40	Sa	3
L	100	40	Sp	4
L	100	40	Sp + R	4
High input (H)	200	80	FD	3
H	200	80	Sa	3
H	200	80	Sp	4
H	200	80	Sp + R	4

samples were taken three days after prewetting under the free drainage. The after-run samples were taken one day after the runs were completed. Samples were taken at five depth intervals: 0 to 2, 2 to 5, 5 to 10, 10 to 15, and 15 to 20 cm. To ensure a proper representation of the profile distribution, soil moisture samples were collected from five different locations and nutrient samples from 12 different locations in each soil pan. Soil moisture samples from a given depth increment in a soil pan were combined in an aluminum can and oven dried at 105°C. Soil samples for determining soil nutrient concentration from a given depth increment in a soil pan were combined, air-dried, sieved (2 mm), and stored for chemical analysis.

Chemical Analysis

Concentrations of NO₃-N in surface runoff water were determined by the cadmium reduction method, and PO₄-P in surface runoff water was measured by the ascorbic acid method (Sparks, 1996). The P in soil was extracted using the Bray-Kurtz P-1 method and determined using the ascorbic acid method. Soil NO₃-N was extracted with KCl solution and measured by the cadmium reduction method (Sparks, 1996).

Calculation of Dissolved Nitrogen and Phosphorus Loss in Surface Runoff Water

For each run, NO₃-N and PO₄-P loss in surface runoff water for the event, L_n (mg), was calculated by the following formula:

$$L_n = \sum_{i=1}^n C_i \times R_i$$

where C_i is NO₃-N or PO₄-P concentration (mg L⁻¹) in surface runoff water at time increment i ; R_i is runoff volume (L) at time i ; and n is the total number of collected samples.

For each run, the average NO₃-N and PO₄-P concentration in surface runoff water, C_n (mg L⁻¹), was calculated as:

$$C_n = \frac{L_n}{TR}$$

where L_n is NO₃-N or PO₄-P loss (mg) and TR is total runoff volume (L).

For each hydraulic gradient treatment under the same fertilizer treatment, the average NO₃-N and PO₄-P concentration in surface runoff water, C_m (mg L⁻¹), was calculated as:

$$C_m = \frac{\sum_{j=1}^p (L_n)_j}{\sum_{j=1}^p (TR)_j}$$

where p is the number of replications in each hydraulic gradient treatment ($p = 3$ or 4), $(L_n)_j$ is NO₃-N or PO₄-P loss (mg), and $(TR)_j$ is total runoff volume (L).

Determination of Statistical Significance

Within each fertilizer treatment, the LSD test was used to determine whether differences in runoff, sediment, concentrations, and losses of NO₃-N and PO₄-P among the four hydraulic gradients were statistically significant at the 95% confidence level. Similarly, within each hydraulic gradient treatment, the LSD test was performed to determine whether differences in the concentrations and losses of NO₃-N and PO₄-P among the three fertilizer treatments were statistically significant.

Table 2. Means and standard deviations (in parentheses) of rainfall, runoff, and sediment loss for 90-min rainfall simulations.

Treatment†	Rainfall	Runoff	Sediment
	mm	mm	g
CFD	74.6 (3.4)a‡	60.7 (5.0)c	53.0 (5.5)c
CSa	75.3 (4.3)a	85.6 (1.3)b	186.0 (94.4)b
CSp		9.2 (1.1)d	0.8 (0)d
CSp + R	74.7 (1.6)a	100.8 (12.8)a	414.2 (119.4)a
LFD	75.9 (3.0)a	65.4 (13.3)c	69.9 (2.7)c
LSa	74.8 (4.1)a	84.1 (4.4)b	197.6 (33.5)b
LSp		10.8 (4.8)d	0.9 (0.1)d
LSp + R	74.4 (2.5)a	96.3 (7.0)a	322.5 (14.8)a
HFD	73.7 (1.7)a	66.8 (11.0)c	61.7 (11.6)c
HSa	74.7 (1.8)a	86.5 (3.4)b	209.3 (19.8)b
HSp		12.8 (0.7)d	0.7 (0)d
HSp + R	74.5 (2.5)a	94.8 (3.4)a	360.1 (10.8)a

† C, control fertilizer treatment (no fertilizer input); L, low fertilizer treatment (40 kg P ha⁻¹, 100 kg N ha⁻¹); H, high fertilizer treatment (80 kg P ha⁻¹, 200 kg N ha⁻¹). FD, free drainage hydraulic gradient; Sa, saturation hydraulic gradient; Sp, artesian seepage without rain hydraulic gradient; Sp + R, artesian seepage with rain hydraulic gradient.

‡ Mean values with a fertilizer treatment followed by any identical letters are not statistically different at the 95% confidence level according to LSD tests.

RESULTS AND DISCUSSIONS

Soil Properties

Soil texture and antecedent soil nutrient content affect soil loss and chemical transport. The soil consists of 58% silt, 20% clay, and 22% sand. The soil contains 1.7% organic matter, 61.3 mg kg⁻¹ NO₃-N, and 0.8 mg kg⁻¹ Bray-Kurtz P-1. The pH in water was 7.0, measured with a 1:1 solid to water ratio on a weight basis.

Rainfall, Runoff, and Sediment Delivery

Rainfall ranged from 67.8 to 80.8 mm (Table 2). Variability of 10% from the target intensity is expected for this type of rainfall simulator. Runoff from the Sa treatment was on average 10 mm greater than the applied rainfall. This could have been due to the release of stored soil water by pressure wave advance (Torres, 2002). This physical process may influence the chemical transport process.

Mean sediment delivery from the Sp treatment was only 0.8 g, and much less than all other treatments. Sediment deliveries from the Sa and Sp + R treatments were statistically greater than those from FD. Sediment deliveries from Sa and Sp + R averaged 2.8 to 3.5 times and 4.6 to 7.8 times greater, respectively, than those from FD. Sediment delivery from the Sp + R treatment was statistically greater than that from the Sa treatment. These data are consistent with prior results showing an increased soil loss from artesian seepage (Huang and Laflen, 1996; Gabbard et al., 1998; Huang et al., 1999; Zheng et al., 2000).

Concentrations of Nitrogen and Phosphorus in Surface Runoff Water

The average concentrations of NO₃-N and PO₄-P in surface runoff water from the FD treatments were less than 0.3 mg L⁻¹ regardless of the fertilizer treatments (Table 3). Except for PO₄-P concentrations under the

Table 3. Means and standard deviations (in parentheses) of concentrations and loss of NO₃-N and PO₄-P in surface runoff for 90-min rainfall simulations.

Treatment	Concentration in surface runoff		Loss in surface runoff			
	NO ₃ -N	PO ₄ -P	NO ₃ -N	N loss as a percentage of N input rate	PO ₄ -P	P loss as a percentage of P input rate
	mg L ⁻¹		kg ha ⁻¹	%	g ha ⁻¹	%
CFD	0.04 (0.03)c‡	0.02 (0.02)b	0.006 (0.003)b		3.62 (4.1)bc	
CSa	1.79 (1.55)bc	0.05 (0.01)a	0.34 (0.06)b		12.6 (2.0)ab	
CSp	75.4 (9.0)a	0.05 (0.01)a	1.57 (0.26)a		1.43 (0.3)c	
CSp + R	8.21 (1.45)b	0.05 (0.03)a	1.90 (0.42)a		16.9 (10.5)a	
LFD	0.08 (0.02)c	0.11 (0.04)c	0.012 (0.003)b	0.01	24.1 (8.9)b	0.06
LSa	2.20 (1.25)c	0.54 (0.36)b	0.42 (0.24)b	0.42	150.7 (103.1)ab	0.38
LSp	529.5 (69.6)a	0.91 (0.39)a	11.4 (4.17)a	11.4	28.9 (7.0)b	0.07
LSp + R	71.8 (30.5)b	0.72 (0.37)ab	15.9 (7.89)a	15.9	230.3 (133.1)a	0.58
HFD	0.09 (0.03)c	0.27 (0.14)c	0.014 (0.006)b	0.01	61.8 (37.3)c	0.08
HSa	8.24 (2.5)c	1.22 (0.14)bc	1.62 (0.56)b	0.81	346.2 (48.8)ab	0.43
HSp	1049.9 (31.5)a	4.69 (0.18)a	30.4 (2.6)a	15.2	252.4 (21.4)b	0.32
HSp + R	135.8 (89.1)b	2.02 (0.83)b	32.9 (13.3)a	16.5	638.9 (286.3)a	0.80

† C, control fertilizer treatment (no fertilizer input); L, low fertilizer treatment (40 kg P ha⁻¹, 100 kg N ha⁻¹); H, high fertilizer treatment (80 kg P ha⁻¹, 200 kg N ha⁻¹). FD, free drainage hydraulic gradient; Sa, saturation hydraulic gradient; Sp, artesian seepage without rain hydraulic gradient; Sp + R, artesian seepage with rain hydraulic gradient.

‡ Mean values with a fertilizer treatment followed by any identical letters are not statistically different at the 95% confidence level according to LSD tests.

control treatment, when the near-surface hydraulic gradients shifted from FD to Sa, then to Sp, concentrations of NO₃-N and PO₄-P increased greatly. For the low and high fertilizer treatments, NO₃-N concentrations in surface runoff water from the Sp and Sp + R treatments were statistically greater than those from the Sa and FD treatments. Under the low fertilizer treatment, NO₃-N concentrations in runoff water from LSp and LSp + R averaged 6618 and 897 times greater than those from LFD, and 241 and 33 times greater than those from LSa, respectively. Under the high fertilizer treatment, NO₃-N concentrations in surface runoff water from HSp and HSp + R averaged 11 665 and 1509 times greater than those from HFD, and 127 and 16 times greater than those from HSa, respectively. The NO₃-N concentrations from Sp and Sp + R were also significantly different. Due to rain water dilution, NO₃-N concentration from the Sp + R treatment decreased by 87% compared with the Sp treatment under the low and high fertilizer treatments.

Concentrations of PO₄-P in surface runoff water from CSa, CSp, and CSp + R were statistically greater than those from CFD. However, PO₄-P concentrations were not statistically different among CSa, CSp, and CSp + R. Under the low and high fertilizer treatments, PO₄-P concentrations in surface runoff water from Sa, Sp, and Sp + R were statistically greater than those from FD. Average PO₄-P concentrations in surface runoff water from LSa, LSp, and LSp + R were 4.9, 8.3, and 6.5 times greater than those from LFD. Similarly, average PO₄-P concentrations from HSa, HSp, and HSp + R were 4.5, 17.4, and 7.5 times greater than those from HFD. Except for the control treatment, PO₄-P concentrations from Sp and Sp + R were greater than those from Sa. Due to rain water dilution, PO₄-P concentrations from Sp + R decreased by 21 and 57%, respectively, compared with Sp under the low and high fertilizer treatments.

Fertilizer application rate greatly influenced NO₃-N and PO₄-P concentrations in surface runoff water. Except for the FD treatment, concentrations of NO₃-N

and PO₄-P in surface runoff water from Sa, Sp, and Sp + R under the high fertilizer treatment were statistically greater than those under the low fertilizer treatment (Table 4). Doubling the fertilizer rate increased NO₃-N and PO₄-P concentrations in surface runoff water by 13 and 145%, respectively, under the FD treatment. Under Sa, Sp, and Sp + R treatments, NO₃-N concentrations with the high fertilizer treatment increased 275, 98, and 89% from the low fertilizer treatment. Compared with the low fertilizer treatment, PO₄-P concentration in surface runoff under the high fertilizer treatment was 126, 415, and 181% greater under the Sa, Sp, and Sp + R treatments, respectively.

Nitrogen and Phosphorus Losses

Average losses of NO₃-N and PO₄-P displayed similar trends as their concentrations (Table 3). Average NO₃-N

Table 4. Comparison of mean NO₃-N and PO₄-P concentrations and losses among the three fertilizer treatments.

Treatment†	Concentration in surface runoff		Losses in surface runoff	
	NO ₃ -N	PO ₄ -P	NO ₃ -N	PO ₄ -P
	mg L ⁻¹		kg ha ⁻¹	g ha ⁻¹
CFD	0.04b‡	0.02b	0.006a	3.62b
LFD	0.08a	0.11ab	0.012a	24.1ab
HFD	0.09a	0.27a	0.014a	61.8a
CSa	1.79b	0.05c	0.34b	12.6c
LSa	2.20b	0.54b	0.42b	150.7b
HSa	8.24a	1.22a	1.62a	346.2a
CSp	75.4c	0.05c	1.57c	1.43c
LSp	529.5b	0.91b	11.4b	28.9b
HSp	1049.9a	4.69a	30.4a	252.4a
CSp + R	8.21c	0.05b	1.90b	16.9c
LSp + R	71.8b	0.72ab	15.9ab	230.3b
HSp + R	135.8a	2.02a	32.9a	638.9a

† C, control fertilizer treatment (no fertilizer input); L, low fertilizer treatment (40 kg P ha⁻¹, 100 kg N ha⁻¹); H, high fertilizer treatment (80 kg P ha⁻¹, 200 kg N ha⁻¹). FD, free drainage hydraulic gradient; Sa, saturation hydraulic gradient; Sp, artesian seepage without rain hydraulic gradient; Sp + R, artesian seepage with rain hydraulic gradient.

‡ Mean values with a hydraulic gradient treatment followed by any identical letters are not statistically different at the 95% confidence level according to LSD tests.

losses from the Sp and Sp + R treatments were statistically greater than those from the FD and Sa treatments. Compared with LFD, runoff from LSp and LSp + R produced approximately 1000 times greater $\text{NO}_3\text{-N}$ loss. Compared with the LSa treatment, $\text{NO}_3\text{-N}$ losses in surface runoff water from the LSp and LSp + R treatments were 27 and 38 times greater. Under the high fertilizer treatment, $\text{NO}_3\text{-N}$ losses from HSp and HSp + R averaged 2171 and 2350 times greater than those from HFD. The seepage treatments, HSp and HSp + R, produced 19 and 20 times more $\text{NO}_3\text{-N}$ than HSp. Even without fertilizer application, average $\text{NO}_3\text{-N}$ losses from CSp and CSp + R were 261 and 316 times greater, respectively, than losses from CFD. However, $\text{NO}_3\text{-N}$ losses from the FD and Sa treatments were not statistically different. Similarly, $\text{NO}_3\text{-N}$ losses from Sp and Sp + R were also not significantly different.

Average $\text{PO}_4\text{-P}$ loss from CSp + R was 4.7 times greater than loss from CFD. Under the low fertilizer treatment, average $\text{PO}_4\text{-P}$ losses from Sp + R and FD were statistically different. The $\text{PO}_4\text{-P}$ loss from LSp + R was 9.6 times greater than that from LFD. However, $\text{PO}_4\text{-P}$ losses from LSp and LFD were not statistical different. Under the high fertilizer treatment, average $\text{PO}_4\text{-P}$ losses from HSp, HSp, and HSp + R were statistically higher than those from HFD. Average $\text{PO}_4\text{-P}$ losses from HSp, HSp, and HSp + R were 5.6, 4.0, and 10.3 times greater, respectively, compared with HFD.

The $\text{PO}_4\text{-P}$ loss from Sp + R was significantly higher than that from Sp under both low and high fertilizer treatments, with a magnitude of 8.0 and 2.9 times greater, respectively (Table 3).

Under the FD treatment, $\text{NO}_3\text{-N}$ loss was approximately 0.01% of the applied N. Under the Sp and Sp + R treatments, $\text{NO}_3\text{-N}$ loss accounted for 11 to 16% of the applied N (Table 3). Seepage flow alone (9.0–13.0 mm) comprised only 9 to 13.5% of the total runoff from the Sp + R treatment, but it appeared to produce most of the $\text{NO}_3\text{-N}$ loss in surface runoff water. These results show that seepage flow could make an important contribution to total chemical transport.

Temporal Trends of Nitrogen and Phosphorus Concentrations

Under the FD treatment, the $\text{NO}_3\text{-N}$ concentrations in runoff were greatest in the initial runoff and decreased gradually during the run (Fig. 3). With seepage flow, a gradual increasing trend of $\text{NO}_3\text{-N}$ in runoff water was observed as the run progressed. These responses were somewhat expected, because under the free drainage treatment, the downward movement of rain water leached $\text{NO}_3\text{-N}$ deeper into the soil profile, while under the seepage treatments, $\text{NO}_3\text{-N}$ in the profile was brought to the surface by the seepage flow. The temporal trend

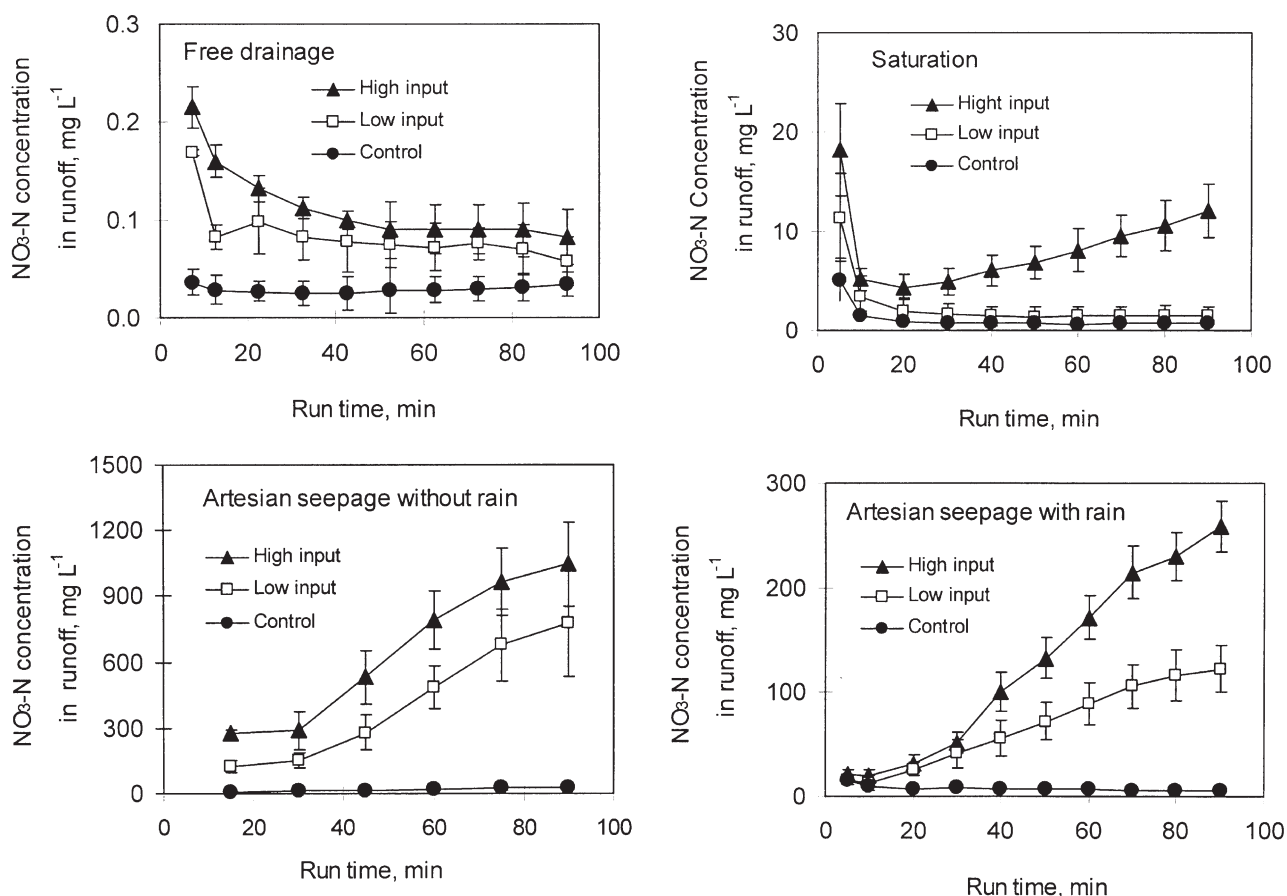


Fig. 3. The $\text{NO}_3\text{-N}$ concentration in runoff during a 90-min run under different hydraulic gradients. Error bars indicate standard derivation.

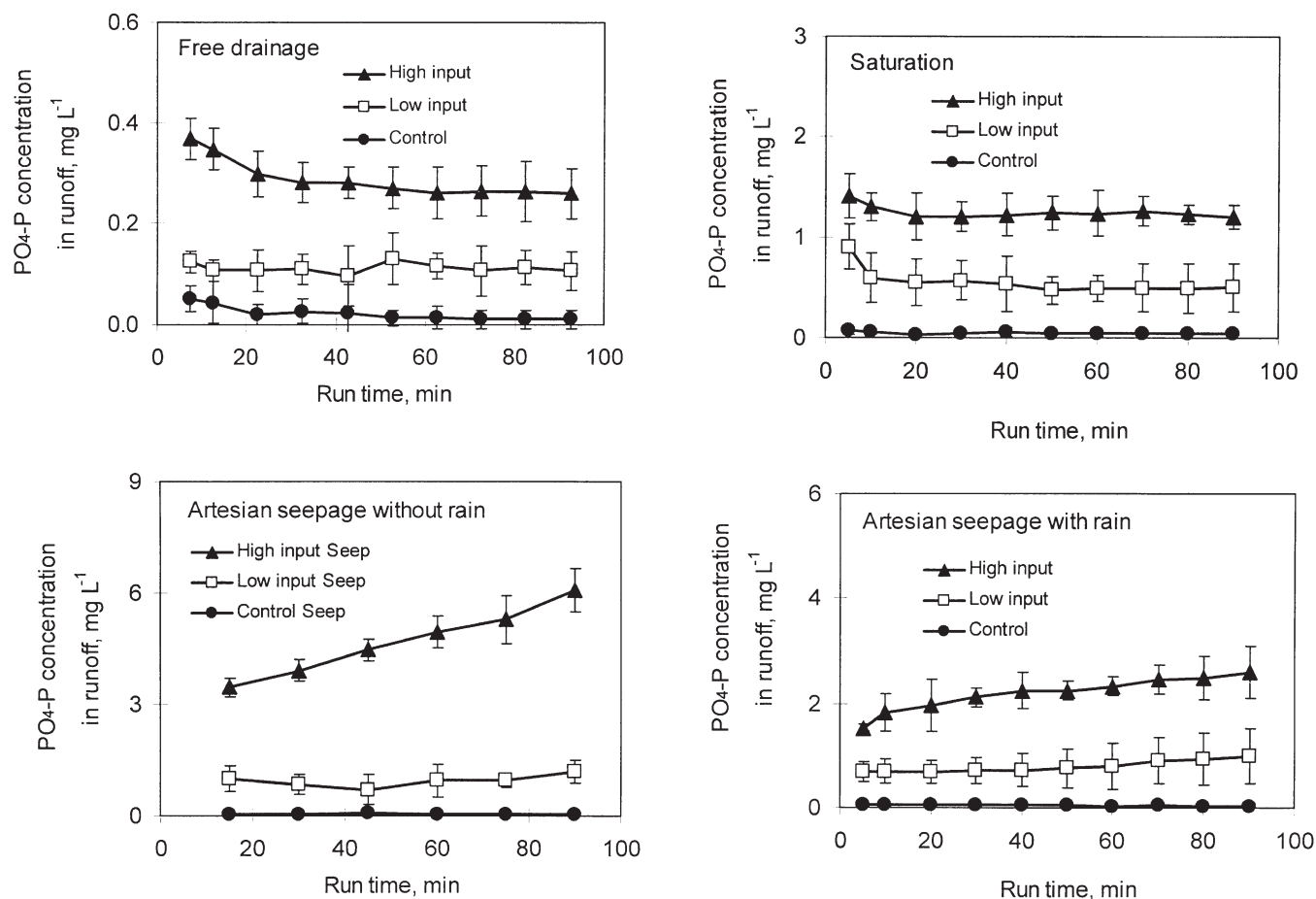


Fig. 4. The $\text{PO}_4\text{-P}$ concentration in runoff during a 90-min run under different hydraulic gradients. Error bars indicate standard deviation.

under the saturation treatment was between those from the drainage and seepage treatments. Without the fertilizer application, the control condition showed little change in $\text{NO}_3\text{-N}$ loss as time progressed for all hydraulic gradients tested. The temporal variation of the $\text{PO}_4\text{-P}$ concentration during the 90-min run was less pronounced than the $\text{NO}_3\text{-N}$ variation (Fig. 4).

These results showed that temporal trends of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ concentrations during the 90-min run were mainly controlled by the near-surface hydraulic gradient and the mobility of chemical in the soil profile. Because $\text{PO}_4\text{-P}$ is less mobile with runoff than $\text{NO}_3\text{-N}$, its loading to surface runoff is not affected by the hydraulic gradient as much as $\text{NO}_3\text{-N}$ is. The increasing trend of $\text{NO}_3\text{-N}$ concentration from Sp and Sp + R under the low and high fertilizer treatments and the increasing trend of $\text{PO}_4\text{-P}$ concentration from HSp and HSp + R implied that a prolonged and extensive artesian seepage event could cause a severe water quality problem.

Distribution of Soil Nitrogen and Bray-Kurtz Phosphorus in the Soil Profile

Concentrations of soil $\text{NO}_3\text{-N}$ and Bray-Kurtz P-1 in the soil profile before and after the run provided additional information for explaining different patterns

of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ losses in runoff water (Table 5). Three days after the 15-mm pre-rain, the highest $\text{NO}_3\text{-N}$ concentration was found at the 5- to 10-cm layer under the low and high fertilizer treatments, and at the 10- to 15-cm layer under the control treatment.

After the run, distributions of $\text{NO}_3\text{-N}$ in the soil profile were quite different depending on the hydraulic gradient. Under the free drainage treatment, $\text{NO}_3\text{-N}$ in the soil was leached deeper into the profile with the downward movement of the wetting front. Most of the $\text{NO}_3\text{-N}$ was found at the 5- to 15-cm depth under the FD treatment. The relative amount of $\text{NO}_3\text{-N}$ at the surface layer was much lower than that in the profile. Distributions of $\text{NO}_3\text{-N}$ conform to prior findings of the subsurface flow being the main $\text{NO}_3\text{-N}$ transport mechanism (Hubbard and Sheridan, 1983; Alberts and Spomer, 1985; Hubbard et al., 1991; Lowrance, 1992). When water was applied from the bottom of the soil pan to either saturate the soil or create the seepage flow, the upward water movement brought $\text{NO}_3\text{-N}$ to the soil surface, causing higher concentrations in the surface soil layer.

The P movement in the soil profiles under all hydraulic gradients was less pronounced than $\text{NO}_3\text{-N}$. Soil Bray-Kurtz P-1 content in the 0- to 2-cm layer under all hydraulic gradients was very high, which could be attributed to fertilizer being applied in the top 2-cm soil layer

and little vertical movement of the applied P with rain water. Soil Bray–Kurtz P-1 in the top 2-cm layer after the 90-min run significantly decreased under the LSa, LSp, LSp + R, HSp, and HSp + R treatments. Under the low fertilizer treatment, soil Bray–Kurtz P-1 content in the top 2-cm layer from LSa, LSp, and LSp + R decreased by 35, 53, and 50%, respectively, compared with the soil Bray–Kurtz P-1 content in the top 2-cm layer before the run. A similar degree of decrease of the soil Bray–Kurtz P-1 content in the surface layer after the 90-min run was observed for HSp, and HSp + R under the high fertilizer treatment. This decline appears to be a result of greater $\text{PO}_4\text{-P}$ loss rates in runoff from these treatments except the LSp treatment.

CONCLUSIONS

This paper presents a laboratory study of near-surface hydraulic gradient effects on losses of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ in surface runoff water under a simulated rainstorm. The results showed a significant increase of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ transport in surface runoff when the downward drainage gradient was removed under the saturation or reversed under the artesian seepage conditions. These results demonstrate the importance of understanding watershed hydrology and its spatial and temporal patterns in predicting areas of high chemical loading potential.

The results of this study also challenge current rainfall simulation methods used in the field to quantify soil erodibility and chemical transport. Field studies are often performed when the fields are dry enough to make the runs, hence under a drainage gradient. Results from prior studies on near-surface hydraulic gradient effects on soil erosion and the current study on $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ transport show that the saturation and artesian seepage conditions can cause greater soil loss and chemical transport than the drainage condition. An examination of soil loss and chemical transport data at various soil moisture conditions allows us to identify critical conditions that would cause water quality problems at field scale.

Although extensive efforts have been made to determine factors contributing to P and N losses, the specific effects of near-surface hydraulic gradient have not been previously quantified. Incorporating the basic understanding of hydraulic factors may contribute to more effective control measures that can minimize the chemical loading to surface runoff at both hillslope and watershed scales.

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Table 5. Means and standard deviations (in parentheses) of soil $\text{NO}_3\text{-N}$ and Bray–Kurtz P-1 distribution in soil profile.[†]

Depth cm	Before					After				
	Before	CFD	CSa	CSp	CSp + R	Before	LFD	LSa	LSp	LSp + R
mg kg^{-1}										
$\text{NO}_3\text{-N concentration}$										
0–2	3.3 (0.9)	1.9 (0.6)	64.0 (2.8)	108.2 (24.3)	92.3 (11.0)	15.6 (2.9)	2.2 (0.2)	134.8 (7.4)	228.4 (36.2)	170.3 (36.9)
2–5	5.7 (1.2)	2.1 (1.1)	134.9 (20.2)	111.3 (24.5)	114.3 (28.3)	39.0 (8.3)	6.4 (0.3)	179.4 (23.1)	221.1 (39.4)	69.5 (3.6)
5–10	52.0 (7.6)	9.4 (1.2)	77.4 (13.7)	55.1 (7.3)	48.3 (4.3)	182.1 (9.5)	31.7 (3.0)	70.3 (9.5)	62.8 (6.6)	17.8 (5.7)
10–15	55.6 (5.6)	86.4 (9.2)	24.2 (4.2)	18.7 (4.4)	13.0 (2.3)	60.5 (9.3)	197.9 (31.2)	18.2 (4.6)	13.9 (2.5)	7.9 (1.7)
15–20	34.3 (7.2)	66.5 (8.2)	13.3 (2.9)	11.8 (2.3)	9.9 (2.2)	41.1 (6.6)	40.9 (5.7)	6.2 (2.1)	9.9 (0.7)	5.2 (0.9)
$\text{Bray-Kurtz P-1 concentration}$										
0–2	1.1 (0.1)	1.0 (0.4)	0.6 (0.1)	0.6 (0.3)	0.6 (0.3)	20.0 (1.7)	20.6 (2.1)	13.0 (3.5)	9.5 (1.0)	10.0 (3.7)
2–5	0.9 (0.1)	0.9 (0.6)	0.7 (0.1)	0.7 (0.4)	0.7 (0.2)	4.5 (2.1)	5.1 (1.5)	3.8 (0.5)	4.6 (0.3)	2.9 (0.8)
5–10	0.7 (0.1)	0.9 (0.5)	0.6 (0.2)	0.6 (0.2)	0.8 (0.1)	0.8 (0.6)	1.0 (0.1)	1.5 (0.3)	0.3 (0.3)	1.1 (0.4)
10–15	0.7 (0.1)	0.6 (0.2)	0.8 (0.1)	0.7 (0.3)	1.0 (0.3)	0.8 (0.2)	0.6 (0.1)	1.4 (0.1)	0.3 (0.2)	1.3 (0.4)
15–20	0.6 (0.2)	0.6 (0.4)	0.9 (0.3)	0.7 (0.3)	0.9 (0.2)	0.7 (0.1)	0.7 (0.3)	1.8 (0.2)	0.4 (0.1)	1.1 (0.3)
HSp										
0–2	1.1 (0.1)	1.0 (0.4)	0.6 (0.1)	0.6 (0.3)	0.6 (0.3)	20.0 (1.7)	20.6 (2.1)	13.0 (3.5)	9.5 (1.0)	10.0 (3.7)
2–5	0.9 (0.1)	0.9 (0.6)	0.7 (0.1)	0.7 (0.4)	0.7 (0.2)	4.5 (2.1)	5.1 (1.5)	3.8 (0.5)	4.6 (0.3)	2.9 (0.8)
5–10	0.7 (0.1)	0.9 (0.5)	0.6 (0.2)	0.6 (0.2)	0.8 (0.1)	0.8 (0.6)	1.0 (0.1)	1.5 (0.3)	0.3 (0.3)	1.1 (0.4)
10–15	0.7 (0.1)	0.6 (0.2)	0.8 (0.1)	0.7 (0.3)	1.0 (0.3)	0.8 (0.2)	0.6 (0.1)	1.4 (0.1)	0.3 (0.2)	1.3 (0.4)
15–20	0.6 (0.2)	0.6 (0.4)	0.9 (0.3)	0.7 (0.3)	0.9 (0.2)	0.7 (0.1)	0.7 (0.3)	1.8 (0.2)	0.4 (0.1)	1.1 (0.3)
HSp + R										
0–2	1.1 (0.1)	1.0 (0.4)	0.6 (0.1)	0.6 (0.3)	0.6 (0.3)	20.0 (1.7)	20.6 (2.1)	13.0 (3.5)	9.5 (1.0)	10.0 (3.7)
2–5	0.9 (0.1)	0.9 (0.6)	0.7 (0.1)	0.7 (0.4)	0.7 (0.2)	4.5 (2.1)	5.1 (1.5)	3.8 (0.5)	4.6 (0.3)	2.9 (0.8)
5–10	0.7 (0.1)	0.9 (0.5)	0.6 (0.2)	0.6 (0.2)	0.8 (0.1)	0.8 (0.6)	1.0 (0.1)	1.5 (0.3)	0.3 (0.3)	1.1 (0.4)
10–15	0.7 (0.1)	0.6 (0.2)	0.8 (0.1)	0.7 (0.3)	1.0 (0.3)	0.8 (0.2)	0.6 (0.1)	1.4 (0.1)	0.3 (0.2)	1.3 (0.4)
15–20	0.6 (0.2)	0.6 (0.4)	0.9 (0.3)	0.7 (0.3)	0.9 (0.2)	0.7 (0.1)	0.7 (0.3)	1.8 (0.2)	0.4 (0.1)	1.1 (0.3)

[†] C, control fertilizer treatment (no fertilizer input); L, low fertilizer treatment (40 kg P ha⁻¹, 100 kg N ha⁻¹); H, high fertilizer treatment (80 kg P ha⁻¹, 200 kg N ha⁻¹); FD, free drainage hydraulic gradient; Sa, saturation hydraulic gradient; Sp, artesian seepage without rain hydraulic gradient; Sp + R, artesian seepage with rain hydraulic gradient.

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